

Estimating Loads of Nutrients, Bacteria, DO and TSS from 71 Watersheds Tributary to South Puget Sound

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Abstract

The Department of Ecology has undertaken a multi-year research project to understand the behavior of south Puget Sound under current and future conditions based on water quality monitoring and hydrodynamic and water quality modeling. To support water quality modeling of the south Sound, we produced daily time series of flows and loads from discrete watershed inflow points required by the three-dimensional EFDC model.

Detailed hydrologic modeling would require tremendous resources. However, approximately 89% of the land area in the model domain has water quality monitoring data available. We developed multiple-regression model coefficients based on available site-specific water quality data to estimate daily parameter concentrations. The approach provides daily time series of parameter concentrations and loads for the parameters of interest: nitrite/nitrate, ammonia, organic nitrogen, orthophosphate, organic phosphorus, total phosphorus, fecal coliform bacteria, total suspended solids, dissolved oxygen, oxygen demand and organic carbon.

To enable load comparisons among watersheds, we normalized loads by tributary area and differences in average annual rainfall as a proxy for discharge. Color-coded maps of these “fair share loads” highlight bays receiving higher normalized loads than others and specific watersheds of interest for a given parameter. These maps may be used to prioritize pollution abatement strategies should reductions be necessary to meet water quality standards in south Puget Sound.

Introduction

The Department of Ecology developed the south Puget Sound nutrient study to address concerns over eutrophication potential from existing and potential point and nonpoint nutrient loads. Overall project objectives are as follows:

- ◆ Identify areas where phytoplankton are naturally nutrient limited, and, thus susceptible to the deleterious effects of eutrophication.
- ◆ Assess seasonal flushing and cycling rates in inlets and bays.
- ◆ Conduct hydrodynamic and water quality investigations to calibrate the 3-D model.
- ◆ Develop nutrient and BOD loads to south Puget Sound from point and nonpoint sources.
- ◆ Develop a 3-D hydrodynamic and water quality model to evaluate the capacity of south Puget Sound to assimilate point and nonpoint source loads and the ability to meet water quality standards.

The water quality model will be used to characterize and evaluate pollutant loads to south Puget Sound. Results may be used to establish Total Maximum Daily Loads (TMDLs) for marine water bodies not meeting water quality standards. The Department of Ecology selected the Environmental Fluid Dynamics Code (EFDC) based on its ability to model complex hydrodynamics, inflows, water-column nutrient cycling, water and sediment equilibrium-partitioning toxic contaminants, salinity and thermal transport, sediment transport, and the nearshore environment (Hamrick 1994). The model requires daily inflows and loads to simulate seasonal and subseasonal variations in south Puget Sound.

Under the National Water Quality Assessment (NAWQA) program, the USGS estimated nutrient transport in rivers tributary to the Puget Sound Basin for the period 1980-93 (Embrey and Inkpen 1998), based on available historical data. Within the south Puget Sound study area, Embrey and Inkpen estimated annual loads of inorganic nitrogen (nitrite, nitrate and ammonia) and total phosphorus for the Deschutes, Nisqually and Puyallup Rivers. However, the study did not include smaller tributaries or direct inflows, which were less important at the scale of the Puget Sound Basin. Yet, these inflows may impact the smaller bays and arms of south Puget Sound significantly.

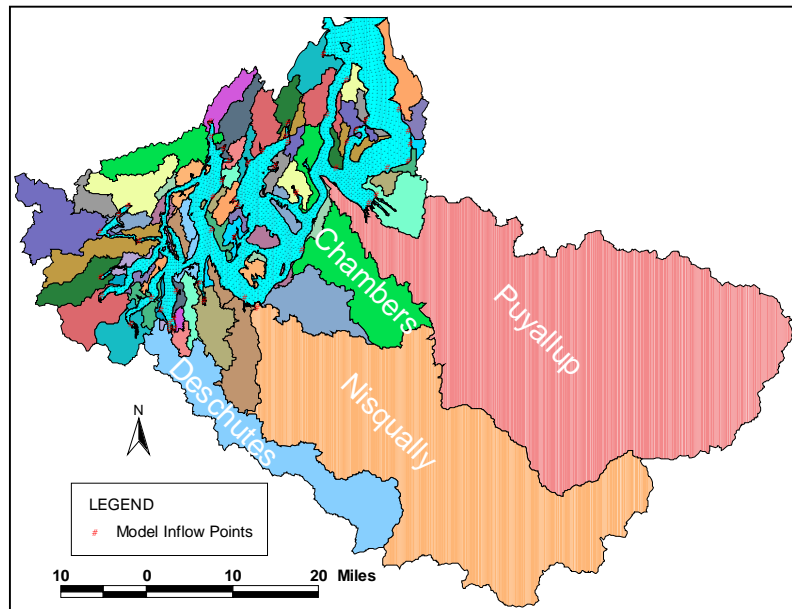


Figure 1. South Puget Sound watersheds and model inflow points.

Using the best available data, we developed site-specific daily flow and load estimates for 71 watersheds tributary to south Puget Sound. Given the convoluted geometry of south Puget Sound and the role of freshwater inflows in hydrodynamics and water quality, we selected inflow locations to represent the distributed nature of the inflows. Figure 1 presents the watershed boundaries and the inflow locations.

Methods

Watershed flow and load estimates were based on existing information, and no additional monitoring was conducted. Figure 2 presents the locations of existing data, drawing from various efforts of the U.S. Geological Survey (USGS), Department of Ecology, Thurston County, Lacey, Olympia, Tumwater, Thurston County (LOTT) Budd Inlet study, and Bremerton-Kitsap County Health District. We estimated both flows and loads using data from the most downstream locations.

Continuous flow gaging covers approximately 66% of the model domain land area and discrete measurements at the time of historical data collection cover an additional 23%. In addition, discrete water quality monitoring covers approximately 89% of the model domain land area (Figure 3). The four major tributaries (Puyallup River, Nisqually River, Deschutes River and Chambers/Clover Creek) represent 2,000 mi², or 71% of the total land area in the model, and have long-term datasets available.

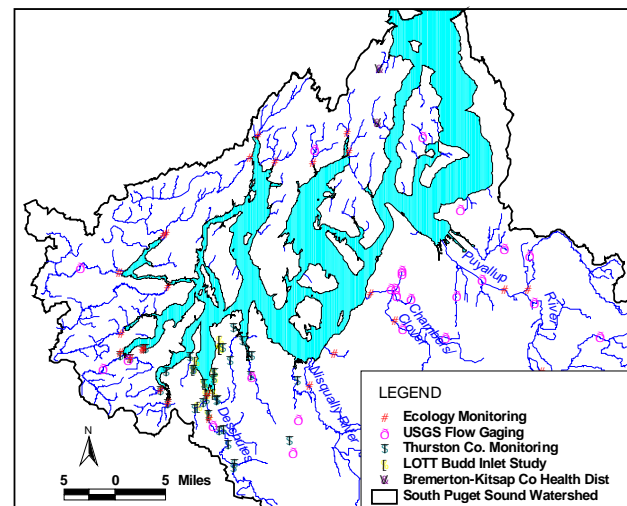


Figure 2. Existing monitoring stations.

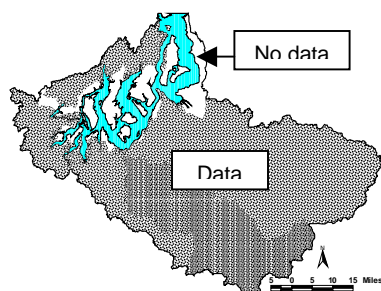


Figure 3. Existing monitoring stations.

Daily loads of the following parameters were estimated for the model calibration period September 1996 through October 1997: nitrite/nitrate, ammonia, organic nitrogen¹, soluble reactive phosphorus, organic phosphorus, fecal coliform, chemical oxygen demand, total suspended solids, dissolved oxygen, and organic carbon (particulate and dissolved). The period of calibration represents above-average precipitation and river discharge. Because discharge was 20 to 35% higher than average (Table 1) for the period of interest, loads will be higher for the calibration period than for a typical hydrologic year.

Table 1. Discharge Characteristics for the Calibration Period

	<i>Deschutes</i>	<i>Nisqually</i>	<i>Puyallup</i>
Average Flow (cfs) for Period of Record	408	1,318	3,318
Average Flow (cfs) for Calibration Period	542	1,775	4,009
% Increase over Long-term Average	33%	35%	21%

Watershed Flows

To estimate flows for watersheds with only discrete flow measurements, we identified a nearby continuously gaged station, drawing from watersheds of similar size, land use and proximity. We normalized the continuous flow record by tributary area and average annual rainfall² and scaled by the area and rainfall of the target watershed. We compared estimated flows to available discrete measurements to verify appropriateness of the approach. The same approach was used for watersheds with no flow measurements, such as the direct inflows.

Watershed Loads

We developed multiple-regression model coefficients specific to each watershed for each parameter. The premise of the regression approach is that parameter concentrations can be predicted based on other parameters, such as flow and the time of year. For example, total suspended solids concentration tends to increase with increasing flow, due to the scouring action of high flows. Nitrite plus nitrate tends to vary seasonally due to primary productivity and senescent cycles in riparian and wetland vegetation.

¹ The water quality model requires organic nitrogen (calculated as total nitrogen minus inorganic nitrogen), organic phosphorus and organic carbon partitioned into dissolved and particulate forms, with particulate further divided into labile and refractory. No monitoring data were available to estimate these partitions for south Puget Sound, and literature-based estimates of 0.5 dissolved, 0.2 refractory particulate and 0.3 labile particulate proportions of organic constituents were used, based on water quality studies elsewhere (Tetra Tech 1999).

² A statewide grid of precipitation was developed by WA DNR Forest Practices Division in 1991.

The multiple linear regression equation used for south Puget Sound loads is given by

$$\log(c) = b_0 + b_1 \log(Q/A) + b_2 \log(Q/A)^2 + b_3 \sin(2\pi f_y) + b_4 \cos(2\pi f_y) + b_5 \sin(4\pi f_y) + b_6 \cos(4\pi f_y),$$

where c is parameter concentration (mg/L or #/100 mL), Q is discharge (m^3/s), A is area tributary to the monitored location (km^2), f_y is year fraction (dimensionless, varies from 0 to 1), and b_i are the best-fit coefficients calculated for each dataset. The regressions were carried out as logarithms of concentration and flow, given the order of magnitude variability in the source data. The flow terms can be based on discharge or area-normalized discharge, Q/A . For single stations, using Q/A has no effect on the regressions. However, in a limited number of cases, data from two adjacent systems with similar conditions were combined to provide a site-specific model appropriate for either (e.g., Mill, Deer and Cranberry Creeks into Hammersley Inlet), and Q/A allows the datasets to be combined.

We developed a simple SYSTAT® (SPSS Inc. ©1997, standard version 7.0.1 for Windows) code to estimate the regression coefficients and calculate appropriate statistical parameters, following the approach³ presented in Cohn et al. (1989). Residuals plots were examined for heteroscedasticity and adjusted R-squared was used to evaluate model fit. Smearing adjustment (Cohn and others 1992) was used to correct for bias due to retransformation from log space. Initial regressions produced several outliers (studentized residual > 3.0). These data points tend to be associated with extreme flow events, obvious errors in the data sets, or an apparently different population. Outliers with studentized residuals greater than 3.0 were removed from the dataset because of the likely errors and differences in the populations.

Where more than one organization collected data at or near the same location, we reviewed the datasets for consistency and merged them, since the regression approach improves with larger datasets. Long datasets were truncated, and only the most recent decade of data used.

Data collection programs used for the regressions relied on regular intervals for sampling, which reduces some sampling bias. Because the programs did not necessarily catch the largest flows, the regression model extrapolates patterns to higher flows, potentially producing significant sources of error. This type of error is more likely for parameters like fecal coliform and total suspended solids, which respond strongly to high flows. The maximum concentration recorded in the monitoring data was used to cap predicted concentration to minimize error due to the extrapolation.

Inflows with Monitoring Data

Of the 71 watersheds tributary to south Puget Sound, 23 watersheds had sufficient monitoring data available to calculate the regression coefficients. Data were compiled in spreadsheets, with all non-numeric values removed. Initially all non-detects were assigned a value equal to the detection limit. We applied the site-specific regression coefficients to estimate daily concentrations from daily flows. Daily loads were calculated from the estimated concentration and average daily flow for each of the parameters of interest for the period September 1996 through October 1997. The continuous daily load estimates were compared against discrete measured data to verify appropriateness of the model. In one case (ammonia from the Nisqually River), the high proportion of non-detects and representation as equal to the detection limit influenced the regression coefficients such that we overpredicted concentrations during low-concentration periods. Ammonia non-detects in the Nisqually River were assigned a value of half the detection limit; new regression coefficients provided a better fit to the measured data.

Monitoring stations may not occur directly at the mouth of each watershed. To account for the loads from the ungauged proportion of the watershed, predicted flows were scaled by differences in watershed area and average annual precipitation. The scaled flows were multiplied by the predicted concentration to develop load estimates of the entire area.

³ The proprietary USGS software Estimator uses the same approach to estimate daily loads from discrete water quality data.

Inflows with Limited or No Monitoring Data

An index water quality station, selected based on size, geographic proximity, precipitation and land use characteristics, provided a method for estimating loads for areas with limited or no monitoring data. Where several were available, regression coefficients from each station were used with the estimated daily average flows at the site to predict concentrations and loads. We used the station producing the best overall fit with the set of monitoring data, rather than different index stations for different parameters. The approach is reasonable given the regional nature of the analysis. Six of the 71 watersheds had limited data that were insufficient for a site-specific regression but that could be used to check the appropriateness of an index station.

While all of the large and moderate inflows to south Puget Sound have at least some water quality data available, many of the small inflows or direct inflows have no data. The station providing the best fit to nearby monitored streams was used as an index for the small, unmonitored inflows. The remaining 42 watersheds had no site-specific data, although they represent only 11% of the model domain. Most of the ungauged watersheds are under 6 mi² with the largest at 34 mi².

Results

Regressions

The adjusted R^2 values varied widely, with generally the highest values achieved for dissolved oxygen and nitrite plus nitrate (median adjusted $R^2 \sim 0.6$ to 0.7) and the lowest values for fecal coliform and ammonia (median adjusted $R^2 \sim 0.3$). Figure 4 presents the predicted and measured loads for the Puyallup River for nitrite/nitrate and ammonia during the period of calculation (the regression was based on data from 1991 to 1997 but only the year of interest for model calibration is presented). The flow and seasonal parameters explain 78% of the nitrite/nitrate concentration variability, but only 23% of the ammonia concentration variability. However, the predicted loads follow the measured loads well, even for ammonia. Thus, although the statistical parameters would suggest a poor fit for the concentration, the variability in the flow exceeds the variability in the concentration, and the loads still match reasonably well. These findings are consistent with Cohn et al. (1992) and Embrey and Inkpen (1998). While the regression model may account for 10 to 50% of the variability in concentration, the overall load model provides satisfactory results, even where the model does not explain most of the variability in concentration (Cohn and others 1992). Figure 5 compares measured with predicted loads for the Puyallup River dataset. While DO and nitrite/nitrate show reasonable agreement, fecal coliform, TSS and phosphorus show significant scatter.

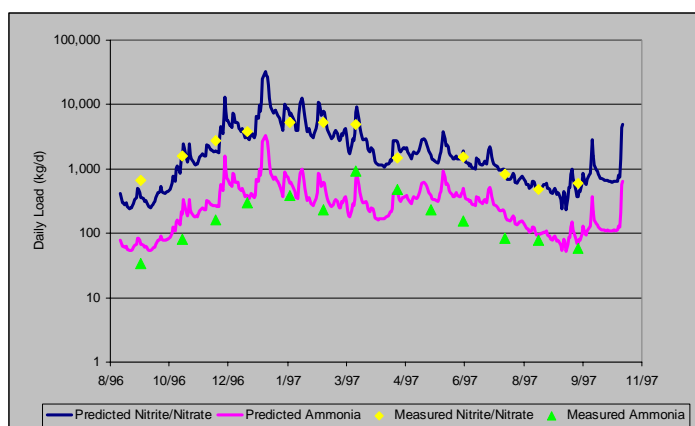


Figure 4. Predicted daily Puyallup River loads.

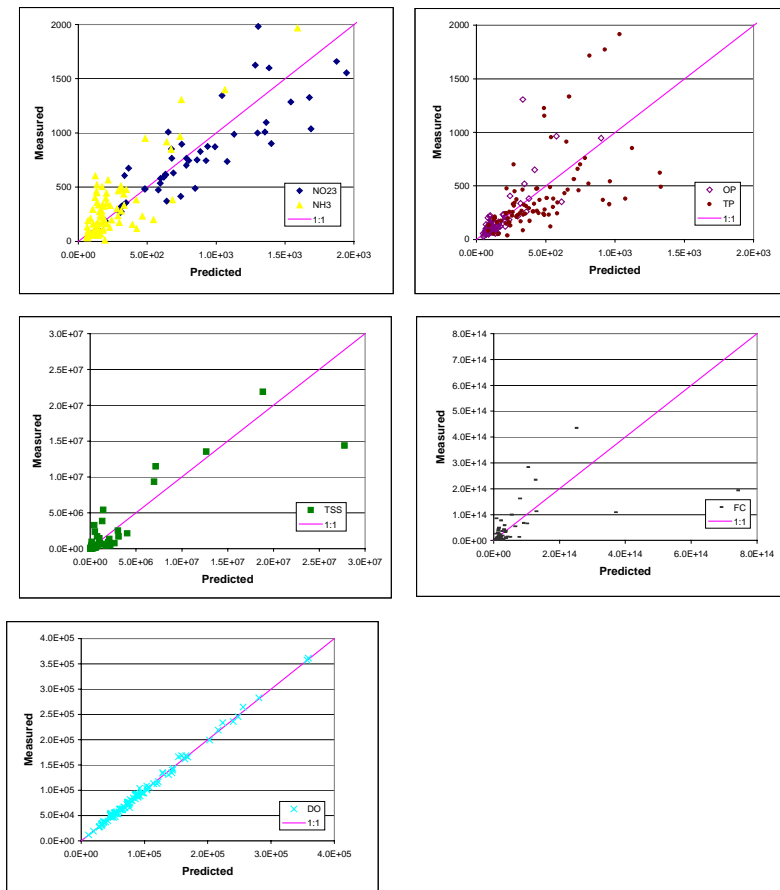
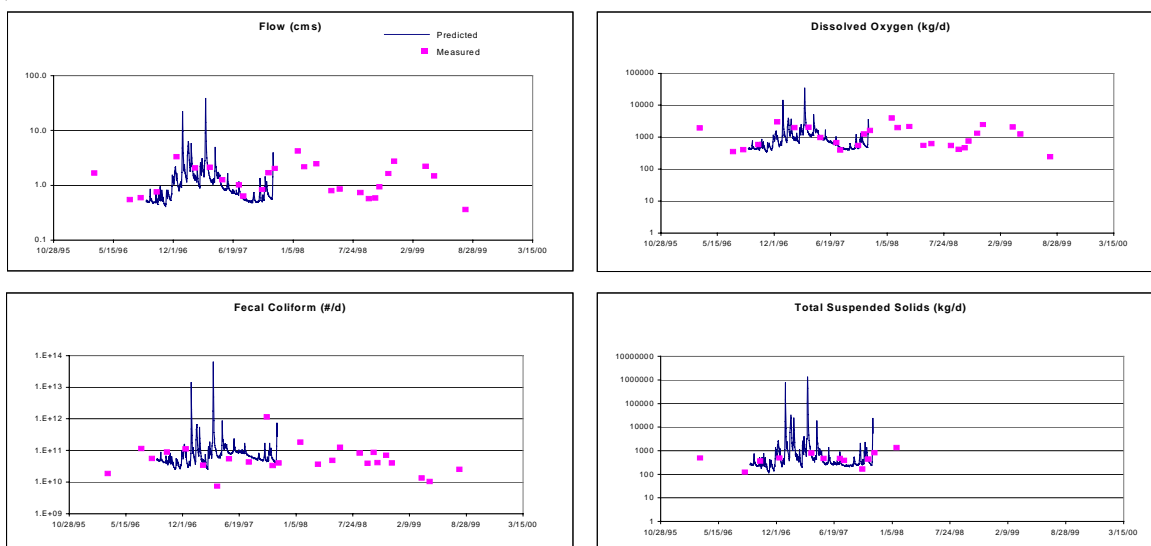


Figure 5. Comparison of predicted and measured loads in the Puyallup River.

Two watersheds tributary to Colvos Passage originally were believed to have no site-specific data, and we estimated loads based on a nearby index station. Afterwards, the Bremerton-Kitsap County Health District provided flow, dissolved oxygen, fecal coliform, and total suspended solids data, which we compared with our estimates. Figure 6 illustrates that our approach provides reasonable flow and load estimates.

Inflow 19 (Curley Creek)



Inflow 20 (Olalla Creek)

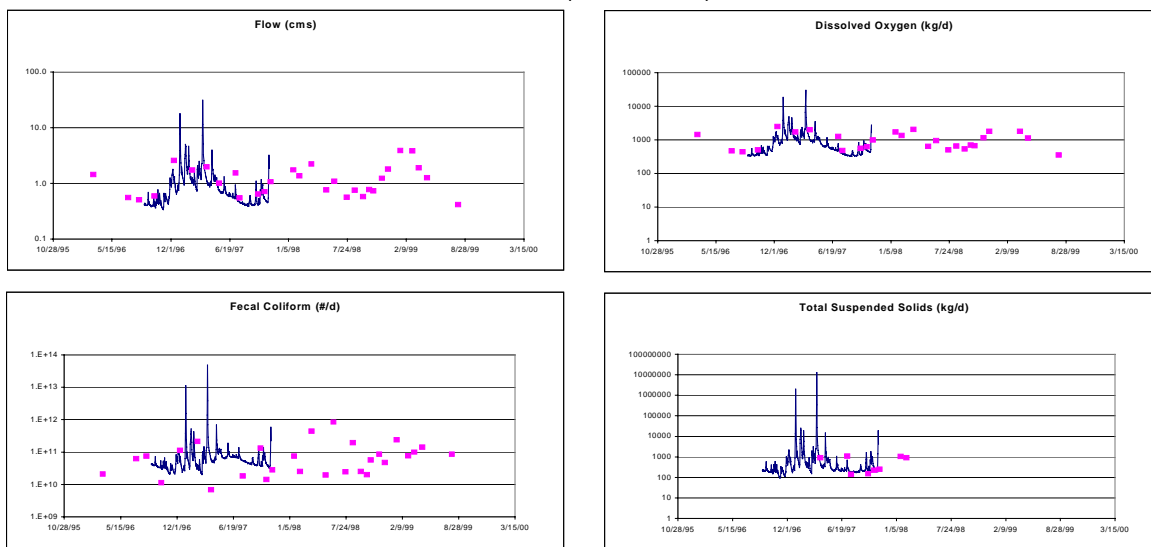


Figure 6. Comparison of predicted and measured flows and loads for unmonitored locations. (Data later provided by Bremerton-Kitsap County Health District.)

Fair Share Loads

The regression coefficients for the various watersheds were used to calculate daily pollutant loads for the water quality model, which will be used to address the impacts of nutrient loading on south Puget Sound water quality. However, the loads generated are also of interest from a watershed standpoint, particularly in comparing among watersheds. We summarized watershed loads two ways: (1) total load to the Sound, and (2) load normalized by relative contribution to the Sound.

Table 2 summarizes the annual average daily watershed flows and loads to south Puget Sound based on the regions identified in Figure 7. Figure 8 presents the same information as percentages of the total inflows to the south Sound. While the Puyallup River occupies 35% of the south Sound watershed area and contributes 43% of the average annual inflow, the river contributes 56% of the ammonia load and over 80% of the annual fecal coliform load.

Table 2. Watershed Flows and Loads by Region (October 1996 through September 1997)

	<i>Chambers</i>	<i>Deschutes/Budd/ Henderson</i>	<i>Northern</i>	<i>Nisqually</i>	<i>Puyallup</i>	<i>Western</i>	<i>Total</i>
Area (sq. mi.)	242	231	249	764	1,009	328	2,823
Discharge (cfs)	483	853	570	3,129	4,335	513	9,883
Nitrite/Nitrate (kg/d)	1,619	1,127	974	2,531	3,014	438	9,703
Ammonia (kg/d)	22	43	42	119	338	38	603
Organic Nitrogen (kg/d)	246	209	138	1,218	1,407	114	3,330
Total Phosphorus (kg/d)	67	106	85	652	1,338	22	2,270
Orthophosphate (kg/d)	24	37	38	72	175	10	356
Organic Phosphorus (kg/d)	43	69	47	580	1,162	12	1,914
Total Organic Carbon (kg/d)	12,121	18,709	2,055	62,852	79,775	3,562	179,074
Chemical Oxygen Demand (kg/d)	11,498	37,915	13,739	69,230	113,507	11,856	257,744
Dissolved Oxygen (kg/d)	12,744	22,756	14,845	86,915	119,473	14,357	271,090
Fecal Coliform (#/d)	1.71E+12	3.68E+12	1.93E+12	2.18E+12	4.42E+13	1.76E+11	5.39E+13
Total Suspended Solids (kg/d)	17,977	123,608	88,620	1,092,260	1,863,631	5,129	3,191,225

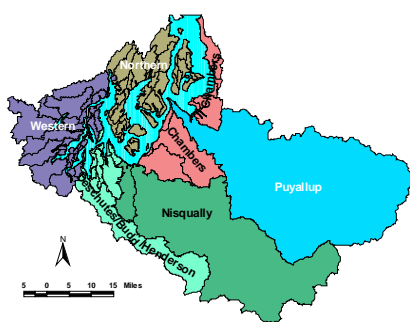


Figure 7. South Puget Sound regions.

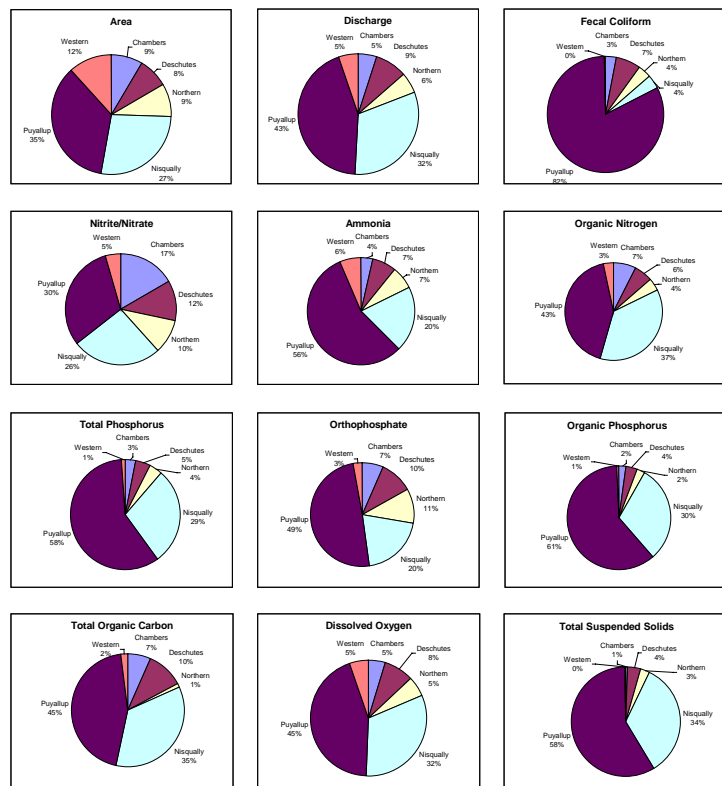


Figure 8. Percent total flows and loads by each region.

While the load magnitudes are important to identify the largest contributors to south Puget Sound, comparisons among watersheds are limited to the size of the watershed as a general proxy, since the larger watersheds tend to contribute the larger flows and loads. However, should loads need to be reduced to achieve water quality standards within Puget Sound, load per unit area may be a better indicator of the most

densely distributed sources. We normalized loads by relative contribution and by relative area, and results are called the fair share loads.

For example, McAllister Creek watershed contributes approximately 280 kg/d of nitrite/nitrate and occupies about 42 mi². The total south Sound tributary area is approximately 2800 mi² and produces an estimated 9,700 kg/d (sum of 71 watershed contributions) of nitrite/nitrate. McAllister Creek contributes 2.8% of the total load, but occupies 1.5% of the watershed area. The fair share load is the load proportion divided by the area proportion, or 1.9. In other words, the McAllister Creek watershed contributes 1.9 times the average areal nitrite/nitrate load compared with the overall south Puget Sound watershed, since fair share loads above 1.0 are higher than average.

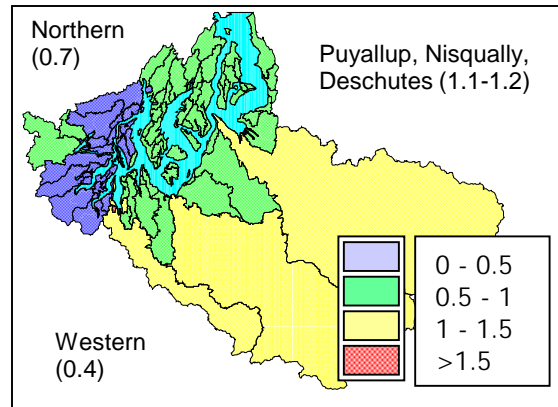


Figure 9. Discharge fair share.

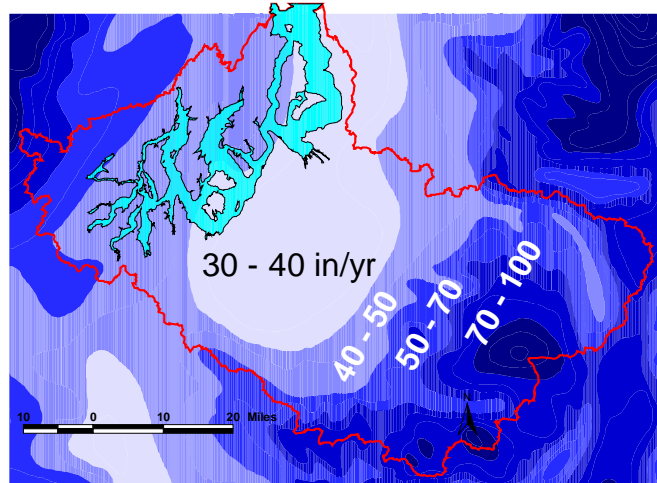


Figure 10. Annual average rainfall contours.

Fair share loads include variations due to discharge. Thus, watersheds with higher than average discharge may have higher than average loads. Figure 9 presents the fair share discharge for south Puget Sound. Watersheds are color coded by the proportion of discharge normalized by the proportion of watershed area. Because the Deschutes, Nisqually and Puyallup Rivers represent 67% of the watershed area, they control the domain-wide average discharge. The resulting fair share discharges are only slightly greater than one; therefore, differences in discharge will not bias fair share loads significantly in the three largest watersheds. The northern and western regions have lower than average discharge, which is consistent with the annual rainfall contours shown in Figure 10. Thus, the fair share loads tend to be lower than average in the northern and western watersheds when compared to the entire project area.

Figure 11 presents the fair share loads for nitrite plus nitrate, ammonia, fecal coliform and total suspended solids. The urban areas of Chambers/Clover Creek and areas tributary to Budd Inlet produce nitrite/nitrate fair share loads >1.5 , indicating loads are 50% higher than the south Sound average. Other regions with elevated nitrite/nitrate are Woodard Creek (tributary to Henderson Inlet), McAllister Creek, and Rocky and Coulter Creek (tributary to Case Inlet). Fair share loads for the direct inflows north of Tacoma are based on the Chambers/Clover Creek results, because of the extensive development in both. Sequatchew Creek also appears to contribute relatively high levels of nitrite/nitrate, based on limited sampling in 1999. Of the three major inflows, the Deschutes River contributes the highest nitrite/nitrate load normalized by tributary area.

Sources of ammonia appear distinct from sources of nitrite/nitrate. The Puyallup River contributes the highest ammonia load in magnitude, but McAllister Creek and two small tributaries to Budd Inlet (Butler Creek and Moxlie Creek) contribute higher fair share ammonia loads. Minter, Burley and Purdy Creeks, tributary to Carr Inlet, contribute fair share ammonia loads just over 1.0.

The Puyallup River dominates the fecal coliform load to south Puget Sound. Several tributaries to Budd Inlet also contribute high fair share loads: Gull Harbor, Ellis/Mission Creeks, Moxlie/Indian Creeks, and Schneider Creek. Thus, Budd Inlet and Commencement Bay receive the highest normalized fecal coliform loads of the south Puget Sound region.

Total suspended solids loads are proportional to the net discharge from the watersheds, with the Puyallup River contributing the highest fair share TSS load, followed by the Nisqually and Deschutes Rivers. The three largest watersheds produce the greatest discharges and receive the highest annual average rainfall in the headwaters (Figure 10).

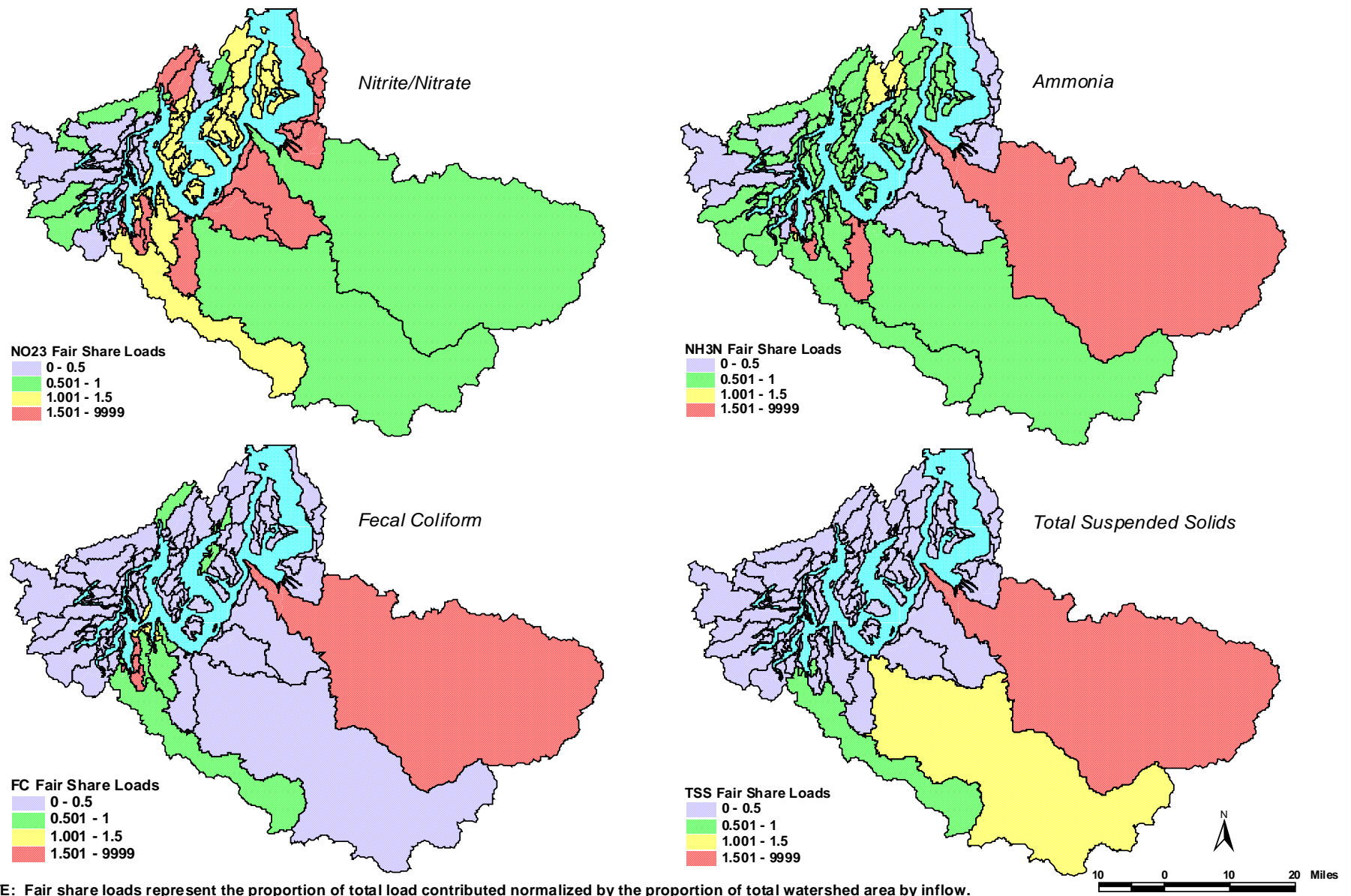


Figure 12 presents the fair share loads for orthophosphate, total phosphorus, organic phosphorus and organic carbon. Sources of orthophosphate do not coincide with significant sources of total phosphorus. The greatest fair share loads of orthophosphate are Ellis/Mission Creeks, Schneider Creek and Moxlie/Indian Creeks, tributary to Budd Inlet; Rocky and Coulter Creeks, tributary to Case Inlet; Burley Creek, tributary to Carr Inlet; and McAllister Creek. Schneider and Burley Creeks are also significant sources of total phosphorus, in addition to the Puyallup River. The Puyallup River provides the highest area-normalized organic phosphorus load to south Puget Sound.

Few organic carbon data were available beyond the Budd Inlet study (Aura Nova and others 1998) and the Puyallup River (USGS, 2000). Only the Schneider Creek watershed in Budd Inlet produced elevated fair share loads.

Discussion

A recent USGS study estimated nutrient loads from major rivers around Puget Sound, including the Puyallup, Nisqually and Deschutes Rivers in south Puget Sound (Embrey and Inkpen 1998). Table 3 compares the results of the USGS study for the period 1980-1993 with results from the present study for October 1996 through September 1997. Average daily flows were significantly higher for the present study and account for most of the differences between load estimates. For example, when normalized by average flow during the periods of analysis, the differences between Puyallup River, the two estimates of average annual inorganic nitrogen and total phosphorus loads were 2% and 13% relative percent difference, respectively. Because the relationship between concentration and flow is nonlinear, flow differences have secondary effects on load estimates.

Table 3. Comparison of Puyallup River Load Estimates

Parameter	USGS (1980 – 1993)	Present Study (Oct. 1996 – Sept. 1997)	
Total Phosphorus	340 tons/year	1,338 kg/d	538 tons/year
Ammonia		338 kg/d	136 tons/year
Nitrite plus Nitrate		3,014 kg/d	1,213 tons/year
Inorganic Nitrogen	950 tons/year	3,352 kg/d	1,349 tons/year

Summary and Conclusions

Site-specific regression models developed from watershed-specific data provide appropriate estimates of regional daily loads tributary to south Puget Sound. The method requires a minimum of approximately 20 data points at any one site; a more robust and representative regression results from extensive representative data. While adjusted R^2 values ranged widely, the regression models capture sufficient variability to represent the load variation from the 71 watersheds. The regression approach is appropriate for the study area, where 89% of the watershed has at least some water quality monitoring data available and 66% of the watershed area has continuous flow gaging.

The daily load estimates can be used to rank watershed-based reductions, if necessary, to meet water quality standards in marine water bodies. Load magnitude is one measure of impact on marine waters; however, larger tributaries generally produce larger loads and sources may be extensive. An alternative approach is the use of fair share loads, which are normalized by area and by differences in average annual rainfall as an indicator of discharge variations. Watersheds contributing greater than average normalized loads may be better to target for load reductions due to more densely distributed sources.

Graphics of the fair share loads illustrate the overall pollutant loading patterns to south Puget Sound, and highlight areas of particular concern. Depending on the results of the water quality modeling effort, these loads may be used to prioritize load reduction efforts.

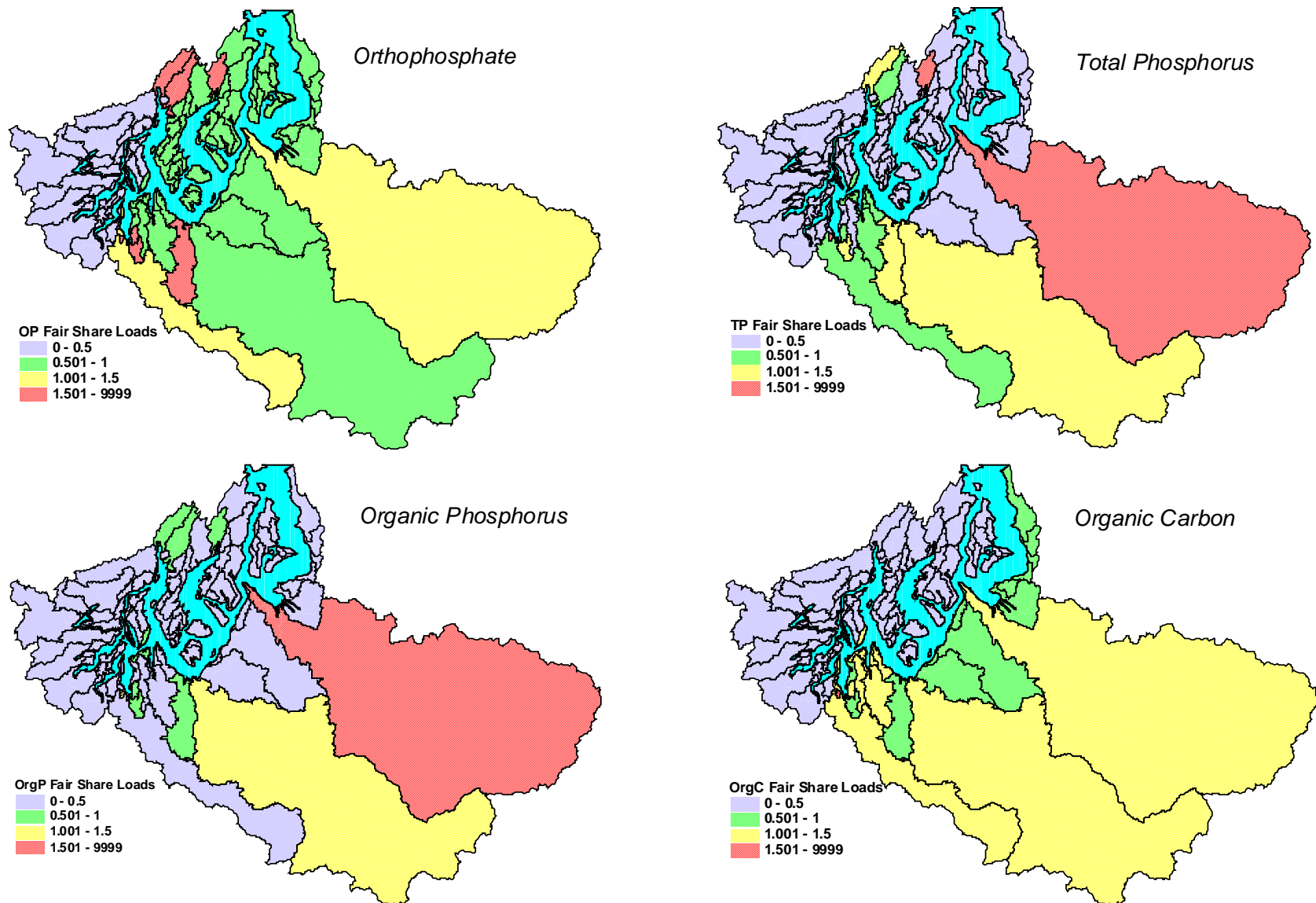


Figure 12. South Puget Sound fair share loads for orthophosphate, total phosphorus, organic phosphorus, and organic carbon.

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While the loads described herein represent the best estimates based on the best available data, they are not meant to be final or static. More recent or additional data collection may improve the regressions in certain bays of interest and for particular parameters.

The Department of Ecology is developing the extent and scope of the second phase of the project, including more extensive water quality model calibration and validation. We hope to calculate confidence intervals for the watershed loads, which will enable sensitivity analyses of the marine water responses to changes in watershed loading.

Acknowledgments

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